Renewable and Sustainable Energy Reviews 16 (2012) 6814–6822

Contents lists available at SciVerse ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Ground source heat pump system: A review of simulation in China

Yanping Yuan *, Xiaoling Cao, Liangliang Sun, Bo Lei, Nanyang Yu

School of Mechanical Engineering, Southwest Jiaotong University, 610031 Chengdu, PR China

ARTICLE INFO

Article history:
Received 4 June 2012
Received in revised form
19 July 2012
Accepted 23 July 2012
Available online 9 October 2012

Keywords:
Ground source heat pump (GSHP)
Ground heat exchanger (GHE)
System simulation
Operation performance
Experimental investigation
Hybrid ground source heat pump (HGSHP)

ABSTRACT

With attractive advantages of high efficiency, energy saving and environmental friendliness, the ground source heat pump (GSHP) system has been used widely in China in recent years. This paper summarizes the analytical solution, numerical solution and experimental investigation of the heat transfer of the ground heat exchanger (GHE), analyzes the simulation model and long-term operation performance of the GSHP system, and introduces the lastest hybrid ground source heat pump (HGSHP) system. In addition, this paper discusses and summarizes the shortages and imperfects of the current research on the simulation of the GSHP system and gives some recommendations for future work.

Contents

1. Introduction . . . 6814
2. Heat transfer model and operation performance of GHE . . . 6814
  2.1. Analytical solution . . . 6815
    2.1.1. Line source theory . . . 6815
    2.1.2. Cylindrical source theory . . . 6815
  2.2. Numerical solution . . . 6817
  2.3. Experimental investigation . . . 6818
3. Simulation model and operation performance of GSHP . . . 6819
  3.1. Coupled model and simulation of GHE and heat pump unit . . . 6819
  3.2. Simulation of HGSHP . . . 6820
4. Discussions and conclusions . . . 6820
Acknowledgements . . . 6820
References . . . 6820

1. Introduction

As the global energy crises and environmental problems become more and more serious, the ground source heat pump (GSHP) technology has showed a trend of booming growth in world due to its attractive advantages of high efficiency, energy saving and environmental friendliness and the GSHP system has become a hotspot in clean energy research. In recent years, great numbers of the GSHP systems have been used in commercial and residential buildings throughout China. According to the Ministry of Science and Technology of China, the total area adopting the GSHP systems will be up to 350 million square meters by the end of 2015 [1]. Now in China, the GSHP technology is in the stage of rapid development.

2. Heat transfer model and operation performance of GHE

Ground heat exchanger (GHE) is an important part of the GSHP system [2]. The heat transfer of the GHE is a very complicated dynamic process. On one hand, the heat transfer of the GHE

* Corresponding author.
E-mail address: ypyuan@home.swjtu.edu.cn (Y. P. Yuan).

1364-0321/$ - see front matter © 2012 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.rser.2012.07.025

Nomenclature

q	heat flux (W/m^2)
T	temperature (K)
c_p	specific heat at constant pressure (J/((kg K))
r	distance from the borehole axis (m)
t	time (s)
m	mass flow rate of the circulating fluid in the U-tube (kg/s)
R	heat transfer resistant ((m K)/W)
L	borehole length (m)
u	velocity of circulating fluid in the U-tube (m/s)
F_o	Fourier constant (–)

Greek letters

λ	thermal conductivity (W/(m K))
a	thermal diffusivity (m^2/s)
β	I integration variable (–)
ρ	density (kg/m^3)

Subscripts

0	initial
f	fluid
s	solid
p	ground heat exchanger
b	borehole wall
in	inlet of the U-tube
out	outlet of the U-tube
a	air
1	inlet branch of the U-tube
2	outlet branch of the U-tube

depends on the buried method, soil characteristics underground hydrological parameters, backfill materials and meteorological data. On the other hand, the heat transfer of the GHE interplays with the operation performance of heat pump unit and the load of buildings [3]. GHEs are divided into two categories: horizontal GHEs and vertical GHEs. Since the horizontal GHE covers larger area and the heat transfer process is considerably influenced by the ground surface temperature and ambient air temperature, this paper focuses on the vertical GHE.

2.1. Analytical solution

2.1.1. Line source theory

In 1948, Ingersoll et al. [4] improved Kelvin's line source theory to solve the heat transfer problem of the GHE. In Ingersoll's theory, the heat transfer of the GHE is simplified as the heat transfer of the heat source which has the same axis of the borehole. The model has several assumptions listed as follows: the ground is an infinite medium with the initial uniform temperature and its thermophysical properties are homogeneous and stable; the heat transfer in the direction of the borehole axis, including the heat flux across the ground surface and down the bottom of the borehole, is neglected; the geometric dimensions of the borehole are neglected and assumed as a line source of the borehole axis.

According to the Ingersoll's line-source theory, the temperature response in the ground due to a constant heat flux is given by:

$$T_s - T_0 = \frac{q}{2\pi\lambda_s}\int_X^{\infty}\frac{e^{-\beta^2}}{\beta}d\beta = \frac{q}{2\pi\lambda_s}I(X) \tag{1}$$

where $I(X)$ is the exponential integral function, $X = r/(2\sqrt{\alpha_s t})$; T_S is the ground temperature, K; T_0 is the initial ground temperature, K; q is the constant heat flux of the line-source, W/m; r is the distance from the borehole axis, m; λ_s is the thermal conductivity of the ground, $W/(m\,K)$, α_s is the thermal diffusivity of the ground, m^2/s; t is the time since the beginning of operation, s; β is integration variable.

The investigation indicated that the third assumption is not reasonable when the time is very short ($t < 5r_b^2/\alpha_s$, several hours in general). For the GHE with constant thermal capacity, the analytical solution shows major errors, especially for short time.

The traditional infinite line source model ignored the influence of the finite length of the borehole and the boundary condition of the ground surface. Fang et al. [5] utilized the Green function method to obtain the temperature response of the finite line heat source in the semi-infinite medium and the temperature response is expressed as:

$$T_s - T_0 = \frac{q}{4\lambda_s\pi}\int_0^L\left\{\frac{erfc\left[\frac{\sqrt{\rho_s{}^2+(z-h)^2}}{2\sqrt{\alpha_s t}}\right]}{\sqrt{\rho_s{}^2+(z-h)^2}} - \frac{erfc\left[\frac{\sqrt{\rho_s{}^2+(z+h)^2}}{2\sqrt{\alpha_s t}}\right]}{\sqrt{\rho_s{}^2+(z+h)^2}}\right\}dh \tag{2}$$

where z is the axis of the vertical direction, h is the integration variable of the finite line heat source.

2.1.2. Cylindrical source theory

2.1.2.1. Cylindrical source theory with a constant heat flux. Cylindrical source theory extends a line source to a cylindrical source with a constant radius. Since the analytical solution of the cylindrical source model has distinct physical meanings, and the cylindrical source theory is more accurate than the line source theory, the cylindrical source theory is more popular in application and plays as the foundation of the great majority of numerical simulation models.

In 1954, Ingersoll et al. [6] developed the analytical solution of the cylindrical source with a constant heat flux and the solution is described as:

$$\Delta T_g = T_w - T_g = \frac{q}{L}\frac{G(Fo,P)}{\lambda_s} \tag{3}$$

where q is the heat flux of the GHE, W; L is the borehole length, m; Fo is Fourier constant; P is the ratio between the distance from the borehole axis and the borehole radius; λ_s is the mean thermal conductivity of the ground, m^2/s. As defined by Carslaw et al. [7], the expression G (Fo, p) is only a function of time and distance from the borehole center.

2.1.2.2. Cylindrical source theory with varied heat fluxes. In actual operation, the heat extracted or released by the GHE varies as the operation conditions. Eq. (1) should be improved since it is derived on the base of the constant heat flux. Bernier [8] utilized the step heat flux to resolve the problem of the varied heat flux. Any load which changes with the time is regarded as the superposition of the thermal effect on the borehole caused by several piecewise linear step heat fluxes. Thus, the solution of temperature distribution is treated as the temperature response of an infinite medium caused by a series of step load with different heat fluxes.

For the time t_n, the temperature difference between far boundary soil and borehole wall is given as:

$$\Delta T_{g,i} = \frac{1}{\lambda_s L}\sum_{i=1}^{n}\sum_{j=1}^{i} q_j\{G[Fo(t_i - t_j - 1)] - G[Fo(t_i - t_j)]\} \tag{4}$$

At the time point of t_n, the temperature depends on both the heat flux of the current time point, and the heat flux of previous time points. The investigation indicates that the heat flux of the current time point plays a major role in the current temperature while the effect of the heat flux of previous time points is much smaller. And the further the previous time point away from the calculation time point is, the smaller the impact is. Thus, calculating the temperature and heat flux of previous time points one after the other is the basis of obtaining the temperature and heat flux of the current time point. Since it is difficult to calculate the performance characteristics of the GHE during a whole year or a longer period, Yavuzturk et al. [9] introduced the term of the load aggregation to deal with the effect of historical heat flux on the current temperature distribution. Given that the effect of the current heat flux is larger than that of the previous heat flux, during simulation, from the time point of t_m, the heat flux is the superposition of the heat flux of the subsequent time points. While for the time point before t_m, the heat flux is considered as the mean heat flux of the previous time points, $q_{mean,m}$, and the superposition is not necessary. The mean heat flux, $q_{mean,m}$, is named as the load aggregation and the period from t_m to t_n is called as the dominant period of the heat influence. Therefore, the temperature of the time point of t_n can be expressed as:

$$\Delta T_{g,i} = T_{g,i} - T_{w,i} = \frac{1}{\lambda_s L}\left\{ q_{mean,i-A}\{G[Fo(t_i - t_0) - G[Fo(t_i - t_{i-A})]\} + \cdots + \sum_{j=1}^{A} q_{i-A+j} \times \{G[Fo(t_A - t_{j-1}) - G[Fo(t_A - t_j)]\} \right\} \tag{5}$$

where A is the number of terms of the superposition. Eq. (5) shows that the number of terms of the superposition in the temperature calculation equation at the time point t_n reduces $A-1$ by introducing the definition of the load aggregation. The temperature mainly depends on the dominant time of the heat influence.

The cylinder source theories with a constant heat flux and variable heat fluxes both assume that for the same time and the same operating mode, the heat flux of buried tubes with different lengths is the same and the heat flux of the left and right side tubes with the same depth is the same, which is inconsistent with the practical condition. In the computational domain coupling the heat transfer of the buried tubes and soil, the temperature gradient of the buried tube wall is the largest. Therefore, the assumption of the cylinder source theory can produce a certain amount of errors. Yavuzturk et al. [10] simplified the boundary condition of the buried tube wall as a constant heat flux and defined that the heat flux in the left side tube is 40% of the total heat flux and the right side is 60%. Although this method has some degree of randomness, it is reasonable in a certain extent because it indicates the heat flux inhomogeneity between the left tube and right tube.

Among domestic research institutions focusing on the analytical solution of the heat transfer of the GHE, the main one is Shandong Jianzhu University. Researchers of the institution divided the heat transfer area into two parts: inside borehole and outside the borehole. The heat transfer process of the soil outside the borehole is treated as the transient heat transfer of the line source. Literatures [11–14], respectively analyzed both the infinite line source model and finite line source model. The heat transfer of the inner of the borehole, including backfill materials, borehole wall and circulating fluid inside borehole, is regarded as a steady heat transfer process [15–19]. On the basis of the energy equilibrium theory, literature [15] adopted the linear superposition principle to establish the two-dimensional heat conduction model during the flowing process of fluid, based on which the dimensionless temperature of the fluid along the dimensionless depth of the borehole in vertical U-tube GHEs was obtained. Literature [16] considered the temperature difference of the fluid along the depth of the borehole, established the quasi three-dimensional heat transfer model of the inner of the borehole and derived the analytical solution of the vertical GHE. Fig. 1 shows the heat transfer network of the borehole in the quasi three-dimensional heat transfer model. Fang et al. [17] also analyzed the heat transfer of the borehole inner of the double U-tube GHE. He utilized the superposition principle to establish the quasi three-dimensional heat transfer model of the borehole inner and derive the analytical solution of the vertical double U-tube GHE. Given that in the heat transfer model of the borehole inner, the borehole wall temperature is one of the most important parameters, he suggested that the integration mean temperature along the whole borehole wall in the depth direction can be treated as the representative temperature of the borehole wall. Literature [19] adopted the virtual heat source method and the linear superposition principle to obtain the steady analytical solution of the inclined GHE.

The quasi three-dimensional heat transfer model of GHE is expressed as:

$$\begin{cases} mc_{pf}\frac{dT_{f1}(z)}{dz} = q_1 + q_{12} = \frac{1}{R_1}(T_b - T_{f1}(z)) + \frac{1}{R_{12}}(T_{f2}(z) - T_{f1}(z)) \\ -mc_{pf}\frac{dT_{f2}(z)}{dz} = q_2 - q_{12} = \frac{1}{R_2}(T_b - T_{f2}(z)) - \frac{1}{R_{12}}(T_{f2}(z) - T_{f1}(z)) \end{cases} \tag{6}$$

Boundary condition:

$$T_{f1}(0) = T_{fin},\ T_{f1}\quad (L) = T_{f2}(L) \tag{7}$$

where c_{pf} is the specific heat of the circulating fluid at constant pressure, J/(kg °C), m is the mass flow rate of the circulating fluid in the U-tube, kg/s; T_{f1} and T_{f2} are the inlet temperature and outlet temperature of the circulating fluid at the depth of z, respectively,°C; T_b is the borehole wall temperature, K; R_1, R_2 and R_{12} are the heat transfer resistance between the fluid and the borehole wall and the equivalent heat transfer resistance between adjacent branch pipes, respectively, $R_1 = R_2$, (m K)/W.

By means of Laplace transform, the dimensionless solution of the fluid temperature distribution along the length direction of two branch pipes are derived and described as:

$$\begin{aligned} \theta_1(Z) &= f_1(Z) + f_2(Z)\frac{f_1(1)+f_2(1)}{f_3(1)-f_2(1)} \\ \theta_2(Z) &= -f_2(Z) + f_3(Z)\frac{f_1(1)+f_2(1)}{f_3(1)-f_2(1)} \end{aligned} \tag{8}$$

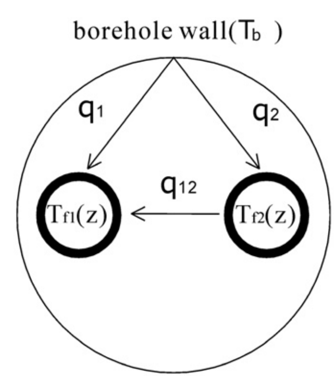


Fig. 1. Heat transfer network of borehole

where

$$Z=\frac{z}{L},\ \theta_1=\frac{T_{f1}(z)-T_b}{T_{fin}-T_b},\ \theta_2=\frac{T_{f2}(z)-T_b}{T_{fin}-T_b},$$

$$R_1^*=\frac{\dot{m}_{pf}^c R_1}{L},\ R_2^*=\frac{\dot{m}_{pf}^c R_2}{L},\ R_{12}^*=\frac{\dot{m}_{pf}^c R_{12}}{L}$$

$$\gamma=\sqrt{\frac{1}{(R_1^*)^2}+\frac{1}{R_1^* R_{12}^*}}$$

$$f_1(Z)=ch(\gamma Z)-\frac{1}{\gamma}\left(\frac{1}{R_1^*+R_{12}^*}\right)sh(\gamma Z)$$

$$f_2(Z)=\frac{1}{\gamma R_{12}^*}sh(\gamma Z)$$

$$f_3(Z)=ch(\gamma Z)+\frac{1}{\gamma}\left(\frac{1}{R_1^*+R_{12}^*}\right)sh(\gamma Z)$$

Yang et al. [20] utilized the cylindrical source theory with varied heat fluxes to solve the temperature distribution of the borehole wall. Wang et al. [21] adopted the cylindrical source theory with varied heat fluxes to establish the coupled model combining the heat pump unit and the GHE and simulated the performance characteristics during a short period of time.

Above studies regarded the heat transfer of the GHE as a pure heat conduction problem and neglected the effect of the advection of the groundwater. The wet soil containing water has two kinds of influence: one is the static effect of the humidity; the other is the effect of infiltration or flow caused by the humidity gradient. The humidity in the ground soil converts the simple heat conduction problem to a complicated problem concerning heat convection and the diffusion of heat and humidity [22]. Diao et al. [23,24] assumed that the ground was the uniform porous medium and the heat transfer of the ground included the heat conduction of the medium and the heat convection of the fluid. The advection of fluid in the porous medium is regarded as a moving heat source and the analytical solution of the two-dimensional temperature distribution caused by the heat source in the infinite medium with advection was resolved.

2.2. Numerical solution

Compared with the analytical solution, although the numerical solution cannot show the distinct physical meaning and the effect of each factor, it can resolve more complicated heat transfer problems of the GHE. And that's why a great number of researchers simulated numerically the heat transfer process of the GHE. Literatures [25–29] adopted an infinite cylinder to be the equivalent of the U-tube GHE and established the coupled thermal transfer differential equations of the GHE. Fig. 2 shows the heat transfer network of the borehole. The corresponding mathematical expressions are as follows:

$$\frac{\partial T_f}{\partial t}+u\frac{\partial T_f}{\partial z}=\frac{q_f}{\rho_f C_{pf}}\quad x\le r_a \tag{9}$$

$$\frac{\partial T_p}{\partial t}=\frac{1}{\rho_p c_{pp}}\left(\frac{1}{r}\frac{\partial}{\partial r}\left(\lambda_p\frac{\partial T_p}{\partial r}\right)+\frac{\partial}{\partial z}\left(\lambda_s\frac{\partial T_p}{\partial z}\right)\right)\quad r_a\le x\le r_b \tag{10}$$

$$\rho_s C_{ps}\frac{\partial T_s}{\partial t}=\frac{1}{r}\frac{\partial}{\partial r}\left(\lambda_s\frac{\partial T_s}{\partial r}\right)+\frac{\partial}{\partial z}\left(\lambda_s\frac{\partial T_s}{\partial z}\right)\quad 0<z<L, r_b\le r\le r_\infty \tag{11}$$

Initial condition:

$$T_s(r,z,0)=T_f(z,0)=T_p(r,z,0)=T_0 \tag{12}$$

Fluid inlet temperature:

$$T_f(z=0,t)=T_{fin} \tag{13}$$

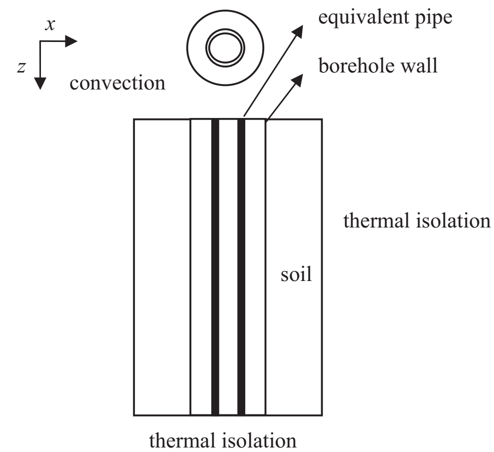


Fig. 2. Heat transfer network of borehole

Boundary condition:

$$\begin{cases}\left.\frac{\partial T_s}{\partial r}\right|_{r=r_\infty}=0\\ \left.\frac{\partial T_s}{\partial z}\right|_{z=L}=0\\ h_a(T_a-T_s(z=0))=\lambda_s\left.\frac{\partial T_s}{\partial z}\right|_{z=0}\end{cases} \tag{14}$$

where u is the velocity of circulating fluid, m/s; r_a and r_b are the equivalent internal and external radius of the ground heat exchanger, respectively, m; r_∞ is the length of far boundary, m. Subscript f, p, and s, respectively stand for fluid, ground heat exchanger and soil.

Tang et al. [30,31] utilized the finite volume method to simulate numerically the temperature and flow distribution of the single U-tube GHE. In the axial direction, the one-dimensional heat convection model is adopted and the circular tube is replaced by the fan-shaped tube in order to obtain convenient gridding. In the depth direction, the two-dimensional heat transfer model is used to calculate the coupled heat transfer performance between the liquid inside the borehole and the soil. The heat transfer models of these two directions are combined into the quasi three-dimensional heat transfer model. During the simulation, the heat transfer in soil is assumed to be conduction only in the horizontal direction; the effect of the bend tube at the bottom of U-tube pipes is ignored, and the fluid at the bottom of two branch pipes is assumed to have the same temperature and opposite direction of velocity. Zhao et al. [32] also adopted the one-dimensional heat transfer model in the vertical direction and the two-dimensional heat transfer model in the horizontal direction. Unlike Tang's simulation method, he developed the heat transfer equations of two leg pipes in the bipolar coordinate system respectively and calculated the actual temperature by overlapping the temperature distributions of the two leg pipes. On the previous basis and in consideration of the interact effect between heat and humidity transfer, literature [33] set up the coupled heat and humidity transfer model of the soil around the U-tube vertical GHE in bipolar cylindrical coordinates. Ren et al. [34] extended the transient two-dimensional heat transfer model of the single vertical U-tube GHE proposed by Rottmayer [35] and analyzed the effect of the heat transfer in the vertical direction and the ground surface temperature on the heat transfer of the GHE. Wang [36] established a mathematic model for a three-dimensional heat transfer temperature field of the vertical GHE in the ground source heat pump system. He presented the layer heat transfer theory, in which the vertical GHE and the surrounding ground are divided into three heat transfer layers, including the saturated heat transfer layer, unsaturated heat transfer layer and none heat transfer layer. Yang et al. [37] developed a heat

exchange model for the vertical U-shaped buried tubes on the base of the element energy balance method. The model had taken account of the liquid temperature change along the flow path, and reflects thermal interference between two tube feet through the introduction of a thermal interference angle and an equivalent heat transfer spacing. Yang et al. [38–41] used both the steady and transient heat transfer method to analyze the heat transfer characteristics inside and outside the borehole by the cylindrical source with variable heat fluxes. Then he developed a heat transfer model of the soil around GHEs by taking soil freezing into consideration and solved the freezing phase change problem by the apparent heat capacity method. He et al. [42] treated the steady heat transfer of the soil temperature field as a discontinuous media problem with mixed boundary values. Based on the nonoverlapping and parallel domain decomposition method of boundary element, the computational domain is divided into two subdomains. In the interface of the two subdomains, the temperature and heat flux are continuous.

In addition, some researchers combined the analytical solution and numerical solution to obtain a simple and quick computational process. Lu et al. [43] divided the computational domain into four parts: liquid inside the borehole, borehole wall, backfill materials and soil of the numerical computational domain and nonnumerical computational domain. The temperature distribution of the liquid inside borehole, borehole wall, backfill materials and soil of numerical computational domain are calculated by the numerical iterative method, while the soil temperature distribution of the nonnumerical computational domain is calculated by the finite-length linear source method. The boundary temperature of the numerical computational domain is determined by the finite-length linear source method, while the heat flux per unit length is obtained by calculating the convective heat transfer between the liquid inside the borehole and the borehole wall. Thus the calculations of both inside and outside the numerical computational domain are coupled.

Yuan et al. [44] divided the computational domain into two parts based on the boundary of the borehole wall. The computational method is the steady analytic solution for the inner of the borehole and the finite volume method for the soil. The simulation models of the two parts are coupled via the borehole wall temperature and the heat flux through the borehole wall. By means of Laplace transform, the outlet temperature of the circulating fluid and the heat per unit length of the soil can be derived. The computational process is divided into three steps. First, calculate the outlet temperature of the circulating fluid and heat per unit length based on the initial borehole wall temperature. Second, calculate the temperature distribution of the soil under the variable heat flux boundary conditions, then calculate the borehole wall temperature, outlet temperature of the circulating fluid and heat per unit length at the current time. Third, use the heat flux of the soil at the current time as the heat flux of the soil for the next time and then to repeat the previous computational process.

Fan et al. [28,45] analyzed the numerical solution of the GHE with groundwater advection. Under the assumption that the velocity of the groundwater was even and the groundwater only flowed along the horizontal direction, the simulation results indicated that groundwater flow had significant influence on the original temperature contour, and the larger the groundwater velocity was, the more significant the effect was.

In practical projects, the GHE is always made of multiple pipes. Different from the heat transfer of the single pipe, the heat transfer of each pipe in multiple pipes influences each other. The heat transfer of multiple pipes is very complicate. According to reported literatures, the heat transfer of multiple pipes mainly focuses on the temperature response of the soil. Most researchers adopted the constant heat flux cylindrical source model [46,47] and discussed the effect of different kinds of arrangements on the temperature distribution of the ground soil [48,49]. In addition, Ding et al. [50] defined the correction factor of multiple pipes, which is the ratio of the heat transfer resistance between multiple pipes and the ground to the heat transfer resistance between the single pipe and the ground. Then he calculated the correction factors of multiple pipes under different operation modes.

Due to the complexity of the geometry of the vertical U-tube GHE and the coupled heat transfer between the fluid inside pipes and the soil, it is impossible and also unnecessary to establish an accurate model to simulate the practical condition to obtain the accurate solution. Hence, all the simulations need a certain simplification. Table 1 summarizes the assumed conditions of parts of the referred literatures. However, there are few reports about the errors of the temperature distribution inside and outside pipes when the simplifications are used to solve the solution.

2.3. Experimental investigation

Experimental investigation is one of the important methods for investigating the GSHP system. Wang et al. [51] carried out comparative experiment for the coaxial and U-tube GHE. Experimental results showed that the heat transfer performance of the coaxial GHE was better than that of the U-tube type. Zhao et al. [52] indicated that the better the insulation of the inner pipe was, the larger the heat extraction of the GHE was. Experimental results also proved that it was feasible to use beads glass ball to imitate the convective soil layer around the GHE Gao et al. [53] analyzed a new GHE with the screw core tube bundle. The experimental results showed that the heat transfer capacity of the new GHE was as high as two times of that of the U-tube GHE. Li et al. [54] conducted experiments on the heat extraction and rejection of the single U-tube and double U-tube vertical

Table 1
Assumed conditions of literatures.

Assumed conditions	No. of literatures											
	9	10	11	12	13	16	17	18	19	20	21	24
Ignoring the heat conduction transfer of soil in the vertical direction	×	×	×	×	×	×	×	√	×	√	×	×
Same flow rate of circulating fluid in any cross-section	√	×	×	×	×	×	√	×	×	√	×	×
Uniform initial temperature of ground	×	√	√	√	√	√	√	√	√	√	√	√
Ignoring the thermal effect of groundwater advection	√	√	√	√	√	√	√	√	√	√	√	√
Ignoring the influence of ambient air temperature fluctuations	√	√	√	√	√	√	√	×	√	√	√	√
Cylindrical heat source	×	×	√	√	√	√	√	×	√	√	×	√
Constant thermal properties of soil	√	√	√	√	√	√	√	√	√	√	√	√
Two-dimensional heat transfer	√	×	×	×	√	√	√	×	×	√	×	√
Steady heat transfer	×	×	×	×	×	×	×	×	×	×	√	×

GHE. The results showed that single U-tube vertical GHE was better than double U-tube vertical GHE in heat extraction and rejection. Zhao et al. [55] tested the U-tube pile GHE and U-tube well GHE in summer and found that the heat extraction rate of the U-tube pile GHE was as large as 116% of that of the U-tube well GHE. At the mean time, the effective thermal radius of the U-tube pile GHE was also larger than that of the U-tube well GHE. Wang et al. [56] carried out comparative investigation on the single HDPE U-shaped tube, single HDPE & stainless steel U-shaped tube and double HDPE U-shaped tube. Xue et al. [57] indicated that the heat flux of the double U-shaped tube is more than that of the single U-shaped tube under both the heat extraction and rejection conditions. Zhao et al. [58] established an in-situ field thermal response test on the basis of the cylindrical heat source model.

3. Simulation model and operation performance of GSHP

3.1. Coupled model and simulation of GHE and heat pump unit

During the operation of the GSHP system, the practical operation performance of the GHE directly affects the performance of the heat pump unit. Thus, in the GSHP system, the dynamic load of the building, the performance of the heat pump unit and the GHEs influence each other.

In China, in terms of the simulation of the GSHP system, the studies focus on the simulation of the heat pump unit or a single component, and the coupling of the building load, ground heat pump unit and GHE. Since the operating principle of the heat pump unit is similar to that of the conventional air conditioning unit, generally, based on the law of mass and energy conservation, researchers establish mathematical models of four main components of the typical heat pump unit, including the compressor, condenser, expansion valve and evaporator and then combine these models to simulate the operation performance of the heat pump unit via the numerical method. Zhou et al. [59] proposed a dynamic lumped parameter model to describe the operating characteristics, and mass and energy conservation of the refrigeration equipment. The parameters of the refrigeration unit in any operating mode are quickly simulated based on a few structural parameters and performance parameters of the working condition. Yang et al. [60] developed a characteristic parameter optimization prediction model, which is used to analyze the operation performance of the water-to-water heat pump with eight undetermined characteristic parameters. Wang [61] regarded the heating output of the heat pump unit as the power function of the flow temperature and flow rate of the source side and load side. By employing the neural network analyzing method, the operation feature curve of the heat pump unit is fitted to analyze the variation of its heating output and cooling output. The operation feature curve also illustrates the coupling relationship between the ground source heat pump unit and the GHE under annual dynamic load. Based on the simulation model of the GSHP system and the building load in a whole year, Yang et al. [62] defined the annual performance factor (APF) of the water-to-water heat pump and used it to study the optimal design and matching mode between different components for the on/off control scheme of the compressor.

Some researchers adopted a more convenient calculation method that the performance of the heat pump unit only depends on the inlet fluid temperature. Therefore, the performance simulation of the total GSHP system is achieved by combining the outlet fluid temperature of the GHE and the operation performance of the heat pump unit and the GHE. Literatures [63–66] fitted the functions of the performance of the heat pump unit and the circulating fluid outlet temperature of the GHE according to the performance data of the heat pump unit given by manufacturers.

At present, there are limited studies focusing on the dynamic coupled model of the GHE and the ground heat pump unit in China. Wang [67] adopted the mechanism modeling method to establish a dynamic mathematical model combining the heat pump unit and the load of the building. Besides, the fuzzy control method is applied in the system. The dynamic operating simulation is carried out with the help of Matlab/Simulink. Qu [68] built a dynamic simulation model by incorporating the ground heat pump model, GHE model and water loop model on the basis of the energy and mass conservation. The simulation model can predict the operating parameters and energy consumption profile of the GSHP system at any time.

Zhao et al. [69] established a prediction model whose key parameters are the heat exchange rate and heat transfer coefficient by using the grey theory. The operational conditions of the unbalance of the load between winter and summer are divided into three working phases: transitional phase, steady phase and declining phase. Grey prediction can provide a quantitative basis for the stable operation and the operation optimization of the GSHP system. At the mean time, experimental investigation [70] was conducted to analyze the long-term operation performance of the GSHP. The experimental results showed that the COP of GSHP system increased in winter and decreased in summer. Ma et al. [71] detected the operation of an actual GSHP project for three consecutive quarters, analyzing the reasons and influence factors of the ground heat unbalance and proposing advices for the optimization.

It is known that the soil is an infinite heat carrier. Centered on the GHE, heat is released/extracted to/from surrounding ground. The load accumulation around the GHE is weakening gradually and the capacity of heat transfer can recover. It can be possible if the actual project is intermittent operation. When the system is closed down, the capacity of heat transfer can be recovered and the performance of the system can be improved. Many researchers investigated the intermittent operation of the GSHP system. Yang et al. [72] found that the intermittent operation can increase the operating efficiency of the GSHP system by the experimental investigation. By controlling the operating patterns of the heat pump unit, Liu et al. [73] studied the changing trend of the water temperature in both the continuous operating mode and intermittent operating mode in order to find out the best approach for optimizing the system operation. Wang et al. [74] indicated that the performance of the GSHP system was influenced by the load of the building. He discussed the feasibility of the intermittent operation of the GSHP system by considering the load characteristics of the building. Zhao et al. [75] carried out long-term numerical simulation on the heat transfer characteristics of the soil around the foundation pile GHEs covering a large land area, presented the concept of heat barrier, and advised that the system analysis should be implemented from the aspects of energy equilibrium and heat barrier-to ensure the whole stability and reliability of the system. Yu et al. [76] measured the actual performance of the GHE with the dissimilar borehole and GHE structures and found that the intermittent operation mode can maintain a better performance of GHEs at an improved value of 33.9% compared with the continuous operation condition. Gao et al. [77–79] analyzed the recovery of the heat transfer capacity of the soil when the GSHP is in intermittent process. They employed the cylindrical model with a constant heat flux to calculate the soil temperature recovery during the intermittent operation, and performed experiments to compare with the ground temperature changing trend in the intermittent operation and continuous operation. They found that with reasonable manual intermittent

control based on the actual operational conditions, the soil heat transfer capacity can be increased. Cui et al. [80] also utilized the superposition principle and analytical solution to simulate the temperature distribution of the soil around the GHE in the intermittent operation. Liu et al. [81] established a two-dimensional heat transfer model in the direction of radius and length, which was applied to calculate the recovery condition of ground temperature in the transitional season (spring). Based on the layout of the multiple pipes and the operating conditions of an actual GSHP project, Liu et al. [82] numerically simulated a soil temperature field where the GHE has operated for 5 years in typical area and under typical operational conditions. and analyzed the simulation results in detail. Yang et al. [83] presented the soil temperature recovery ratio to estimate the recovery status of the soil temperature.

3.2. Simulation of HGSHP

To deal with the performance decline of the GSHP system which is caused by the unbalanced building load between winter and summer, the HGSHP with assistant cooling devices or heating devices has appeared. At present, most studies mainly focus on the computational analysis of the operation mode, optimization and performance of the system. Wang et al. [84,85] simulated and evaluated the operation performance of the assistant cooling-source heat pump system in the hot summer and cold winter region, and adopted the corrected design method to maximize its performance and indicated that considering the initial investment and operating cost, the assistant cooling-source heat pump system is superior to the GSHP system without assistant cooling. Yang et al. [86,87] developed a mathematic model for the solar-earth source heat pump system (SESHPs) on the basis of the component models, and simulated numerically the performance of alternative SESHPs. Ma et al. [88–93] presented the integrated frozen soil cool storage-GSHP system. Through establishing the mathematic model of the soil charge and discharge, the operation performance of the integrated system is simulated numerically and the energy loss through the soil charge and discharge is analyzed. In addition, literatures [94–96] have investigated the control strategies, design procedures and optimization designs of different kinds of HGSHP systems and provided general methodologies and advices for optimal design and operation of such HGSHP systems.

4. Discussions and conclusions

During the recent few decades, great deals of GSHP systems have been widely used in China. In this paper, most heat transfer simulation models currently available for vertical GHEs have been described in details; the experimental investigation, as one of the important methods for investigating the performance of the GSHP system, has been reviewed; and simulation models aiming to evaluate and optimize the energy performance of the GSHP system have been referred as well. Finally, this paper focuses on the simulation of the HGSHP system with assistant cooling devices or heating devices since the HGSHP system is the tendency of the GSHP.

It can be seen from the overview that Chinese researchers have obtained the following achievements. First, the traditional infinite line source model ignored the influence of the finite length of borehole and the boundary condition of the ground surface. On the basis of the infinite line source model, Chinese researchers utilized the Green function method to obtain the temperature response of the finite line heat source in the semi-infinite medium. At the same time, the equivalent heat transfer resistances of the single U-tube GHE and double U-tube GHE were calculated, and the quasi three-dimensional heat transfer model of the vertical U-tube GHE was derived by using the superposition principle. And the integral average temperature along the length direction of the borehole wall was proposed to be adopted as the representative temperature of the borehole wall. For the problem of the groundwater advection, the advection of the porous medium was regarded as the moving heat source problem and the analytical solution of the temperature response caused by the line heat source in the infinite medium with advection was resolved.

Second, Chinese researchers proposed computational models by combining the analytical solution and numerical solution in order to give considerations to both the computation speed and accuracy. The computational domain is divided into two parts based on the boundary of the borehole wall. The computational method is the steady analytic solution for the borehole inner and the finite volume method for the soil. The simulation models of the two parts are coupled based on the borehole wall temperature and the heat flux through the borehole wall.

Although a great number of researches have focused on the development and application of the GSHP system, there are still a few aspects that need further investigation to broaden and strengthen the applicability of the GSHP technology:

(1) The vertical GHEs penetrate through different structures of geological layers. Both the multi-layered soil and groundwater have great influences on the heat transfer performance of vertical GHEs. However, most heat transfer models of GHEs cannot take into the effect of multi-layered soil and groundwater. Therefore, the studies on the effects of these two factors should be strengthened to improve current heat transfer models.
(2) In actual projects, GHEs are always made up of multiple pipes. It is difficult to accurately simulate the instantaneous performance of larger-scale GHEs because the simulating calculation is very complex and time-consuming. There are few reports aiming to optimize the operation strategies of multiple pipes in partial load. It is worth to carry out investigations on this issue in the future.
(3) During the operation of the GSHP system, the building load, the heat pump unit and the GHE influence each other. So, it is necessary to set up the coupled heat transfer model of the ground source heat pump system to obtain more accurate dynamic performance of the system.

Acknowledgements

The work is supported by Natural Science Foundation of China (NO: 50978220), Program for New Century Excellent Talents in University of Ministry of Education (NO: NCET-11-0714) and Program for Outstanding Young Science Leaders of Sichuan Province (NO: 2010A14-449).

References

[1] Ministry of Science and Technology, The technique and application of geothermal energy utilization in China, 2012.
[2] Yuan YP, Lei B, Yu NY, Cao XL, Zhang D. Heat transfer of ground heat exchanger for GSHP (1): a review. Heating Ventilating & Air Conditioning 2008;38(4):25–32.
[3] Yuan YP, Lei B, Yu NY, Cao XL, Zhang D. Heat transfer of ground heat exchanger for GSHP (2): complete mathematical description of heat transfer course. Heating Ventilating & Air Conditioning 2009;39(7):9–12.
[4] Ingersoll LR, Plass HJ. Theory of the ground pipe heat source for the heat pump. Heating, Piping & Air Conditioning 1948;20:119–22.

[5] Zeng HY, Diao NR, Fang ZH. A model of finite-length linear heat-source for the vertical embedded pipe of a ground-source heat Pump. Journal of Engineering for Thermal Energy & Power 2003;104(18):166–9.
[6] Ingersoll LR, Zoeble OJ, Ingersoll AC. Heat conduction with engineering.Geological and other application. New York: McGraw-Hill; 1954.
[7] Carslaw HS, Jaeger JC. Conduction of heat in solids. 2nd ed. Oxford: Claremore Press; 1959.
[8] Bernier M. Ground-coupled heat pump system simulation. ASHRAE Transactions 2001;107(1):605–16.
[9] Yavuzturk C, Spitler JD. A short time step response factor model for vertical ground loop heat exchangers. ASHRAE Transactions 2001;105(2): 475–85.
[10] Yavuzturk C, Spitler JD, REE SJ. A transient two-dimensional finite volume model for the simulation of vertical U-tube ground heat exchangers. ASHRAE Transaction 1999;105(2):465–74.
[11] Cui P, Diao NR, Fang ZH. Analysis on discontinuous operation of geothermal heat exchangers of the ground-source heat pump systems. Journal of Shandong Institute of Architecture and Engineering 2001;16(1):387–90.
[12] Zeng HY, Diao NR, Fang ZH. Analysis on steady-state temperature field around a vertical borehole in geothermal heat exchangers. Journal of Shandong Institute of Architecture and Engineering 2002;17(1):60–3.
[13] Zeng HY, Fang ZH. A fluid temperature model for vertical U-tube geothermal heat exchangers. Journal of Shandong Institute of Architecture and Engineering 2002;17(1):7–11.
[14] Fang ZH, Diao NR, Zeng HY. Heat transfer analysis of ground heat exchangers. Journal of Engineering Thermophysics 2004;25(4):685–7.
[15] Cui P, Diao NR, Fang ZH, Sun CL. Heat transfer model and thermal resistance calculation of U-shape buried pipe of geothermal heat exchangers. Heating Ventilating & Air Conditioning 2003;33(6):108–10.
[16] Zeng HY, Diao NR, Fang ZH. Heat transfer analysis of boreholes in vertical ground heat exchangers. International Journal of Heat and Mass Transfer 2003;46:4467–81.
[17] Zeng HY, Fang ZH. A heat transfer model for double U-tube geothermal heat exchangers. Journal of Shandong Institute of Architecture and Engineering 2003;18(1):11–7.
[18] Zeng HY, Diao NR, Fang ZH. Analysis of the heat transfer inside a borehole of vertical ground heat exchangers. Acta Energiae Solaris Sinica 2004;25(61): 399–405.
[19] Cui P, Yang HX, Fang ZH. Heat transfer analysis of ground heat exchangers with inclined boreholes. Applied Thermal Engineering 2006;26:1169–75.
[20] Yang WB, Shi MH. Numerical simulation on heat transfer process in U-bend ground heat exchanger of ground source heat pump. Journal of Southeast University(Natural Science Edition) 2007;37(1):78–83.
[21] Wang JG, Ma YT, Zhang ZP. Operating performance simulation of ground source heat pump system. Journal of Engineering Thermophysics 2003;24(3): 36–366.
[22] Gao Q, Li M, Yu M, Xuan ZH, Qiao G. Heat transfer influenced by containing water in wet soil. Journal of Thermal Science and Technology 2005;4(2): 136–40.
[23] Diao NR, Li QY, Fang ZH. Heat transfer in ground heat exchangers with groundwater advection. International Journal of Thermal Sciences 2004;43: 1203–11.
[24] Li M, Diao NR, Fang ZH. Analytical solution of seepage flow in a confined aquifer with a standing column well. Journal of Shandong Institute of Architecture and Engineering 2006;21(1):1–5.
[25] Zhou YS, Zhang X, Chen PL. Heat transfer and reasonable distance analysis for vertical U-tubes used in GSHP. Journal of Donghua University (Natural Science) 2006;27(5):10–5.
[26] Zhang KL, Wang RZ, Wang LQ. Theoretical research of vertical buried ground source heat pump. Fluid Machinery 2001;29(9):57–60.
[27] Li YD, Wei XX. Experimental and numerical simulation of horizontal ground coil heat exchanger in cooling mode. Journal of Hunan University (Natural Science) 1999;S1:58–63.
[28] Fan R, Ma ZL. Heat transfer analysis of geothermal heat exchanger under coupled conduction and groundwater advection. Acta Energiae Solaris Sinica 2006;27(11):1155–62.
[29] Yu YS, Ma ZL, Yao Y. Simulative research on soil thermal storage in integrated soil thermal storage and ground-coupled heat pump system. Acta Energiae Solaris Sinica 2004;25(6):820–4.
[30] Tang ZW, Shi XY, Huang JH, Wang XT. Computer simulation of the U-tube ground heat exchanger for GSHP. Journal of Beijing University of Technology 2006;32(1):62–6.
[31] Huang JH, Shi XY, Tang ZW. Pseudo 3D model of ground heat exchanger for GSHP. Journal of China Agricultural University 2004;9(5):51–4.
[32] Zhao J, Zhang CL, Li XG, Yu LY, Song DK. Three-dimensional heattransfer model and experimental analysis of U-pipe heat exchanger. Acta Energiae Solaris Sinica 2006;27(1):63–6.
[33] Li XG, Li W, Li LM. Theoretical model and simulation on heat and moisture transfer around U-vertical underground heat exchanger in double cylinder coordinates. Acta Energiae Solaris Sinica 2008;29(9):1067–71.
[34] Ren XH, Sun CW, Hu YW. A three-dimensional numerical model and experimental research for U-tube ground heat exchanger in heating operation. Journal of Chongqing Architecture University 2004;26(5):90–5.
[35] Rottmayer SP, Beckman WA, Mitchell JW. Simulation of a single vertical U-tube ground heat exchanger in an infinite medium. ASHRAE Transactions 1997;103(2):651–9.
[36] Wang Y, Liu F, Fu XZ. Design of vertical ground heat exchangers based on a layer heat transfer theory. Heating Ventilating & Air Conditioning 2007;37(9): 35–9.
[37] Yang WB, Shi MH. A study of heat exchange characteristics of vertical U-shaped embedded tubes based on an element energy balance method. Journal of Engineering for Thermal Energy and Power 2007;22(1):96–100.
[38] Yang WB, Shi MH. Numerical simulation on heat transfer process in U-bend ground heat exchanger of ground source heat pump. Journal of Southeast University (Natural Science Edition) 2007;37(1):78–83.
[39] Yang WB, Shi MH. Study on cylindrical source theory based on vertical U-tube ground heat exchangers and its application. Journal of Refrigeration 2006;27(5):51–7.
[40] Yang WB, Shi MH, Liu GY, Chen ZQ. A two-region simulation model of vertical U-tube ground heat exchanger and its experimental verification. Applied Energy 2009;86:2005–12.
[41] Yang WB, Shi MH, Liu GY, Chen ZQ. Study on freezing characteristics of soil around ground heat exchangers of ground-source heat pumps based on apparent heat capacity method. Heating Ventilating & Air Conditioning 2008;38(4):6–10.
[42] He YY, Li MJ, Ma JJ. Application of boundary element—domain decomposition method in ground temperature field around U-vertical buried pipe. Journal of Chongqing Institute of Technology (Natural Science) 2008;22(9):28–31.
[43] Lu Z, Lian ZW, Liu WW, Lan L. Numerical simulation and linear heat source integrated model of vertical embedded pipe for ground source heat pump. Journal of Shanghai Jiaotong University 2008;42(3):409–14.
[44] Yuan YP, Lei B, Cao XL, Zhang D. Heat transfer of ground heat exchanger for GSHP(3):transient heat transfer characteristic of U-type ground heat exchanger with variable heat flow boundary. Heating Ventilating & Air Conditioning 2009;39(2):10–5.
[45] Fan R, Jiang YQ, Yan Y. A study on the performance of a geothermal heat exchanger under coupled heat conduction and ground water. Energy 2007;23:2199–209.
[46] Li XG, Zhao J, Zhou Q. Inner heat source model with heat and moisture transfer in soil around the underground heat exchanger. Applied Thermal Engineering 2005;25:1565–77.
[47] Gao Q, Li M, Yan Y. Operation strategy on heat transfer enhancement in the underground multi-boreholes. Acta Energiae Solaris Sinica 2006;27(1): 83–99.
[48] M Li, Q Gao, Study on the simulation of multi-boreholes and the effect of their configurations, In: Proceedings of national HVAC & refrigeration academic conference, 2004.
[49] Gao Q, Li M, Yan Y. Effect on ground source field heat transfer of original earth temperature and configuration of multi-boreholes. Journal of Thermal Science and Technology 2005;4(1):34–40.
[50] Ding Y, Li BZ, Lu J, Sun CW, Liu XY. Design of buried heat exchangers for ground-source heat pump systems(2). Heating Ventilating & Air Conditioning 2005;35(11):76–9.
[51] Wang Y, Fu XZ. Research on coaxial heat exchangers for ground source heat pump. Journal of Chongqing Jianzhu University 1997;19(5):13–7.
[52] Experimental investigation and theoretical model of heat transfer of saturated soil around coaxial ground coupled heat exchanger, Applied Thermal Engineering 28 (2008) 116–125.
[53] Gao Q, Ding M, Bai JY, Li M. Enhanced heat transfer for increasing utilization of ground energy. Acta Energiae Solaris Sinica 2003;24(3):307–10.
[54] Li XG, Chen Y, Chen ZH, Zhao J. Thermal performances of different types of underground heat exchangers. Energy and Buildings 2006;38:543–7.
[55] Li XG, Chen ZH, Zhao J. Simulation and experiment on the thermal performance of U-vertical ground coupled heat exchanger. Applied Thermal Engineering 2006;26:1564–71.
[56] Wang XT, Tang ZW, Ma FC. Contrastively experimental research of three vertical geothermal heat exchangers with heating in winter. Journal of Engineering Thermophysics 2006;27(2):85–8.
[57] Xue YW, Ji M, Li XG, Zhao J. Heat performance research and economical analysis of single U shaped and double U shaped vertical borehole heat exchanger. Acta Energiae Solaris Sinica 2006;27(4)4l0-414 2006;27(4).
[58] Zhao J, Duan JQ, Song ZK, Li LH. A method for in situ determining underground thermal properties based on the cylindrical heat source model. Acta Energiae Solaris Sinica 2007;28(9):934–6.
[59] Zhou YS, Zhang X, Chen PL. Numerical simulation and experimental study on heating operation of GSHP. Journal of Donghua University (Natural Science) 2002;28(1):5–9.
[60] Yang WB, Shi MH. Discussion on simulation model of a water-to-water heat pump based on characteristic parameters optimization prediction. Fluid Machinery 2007;35(8):80–6.
[61] Wang Y. Study on performance of ground source heat pumps under dynamic load. Chongqing: Chongqing University; 2006.
[62] Yang Z, Zhao HB, Hu YF, Wu K. Research on annual performance factor of water–water heat pump system. Journal of Refrigeration 2006;27(3):24–9.
[63] Yang WB, Shi MH. Optimization of solar-ground source heat pump systems based on genetic algorithm. Heating Ventilating & Air Conditioning 2007;37(2):12–7.
[64] Yu YS, Ma ZL, Lian LM. Simulation research on operation condition of the solar energy heat pump system. Fluid Machinery 2004;32(5):65–9.
[65] Wang HJ, Li XG, Zhao J, Li LX, Dong YP. Experimental study and analysis on heating operation of GCHP. Fluid Machinery 2003;31(12):51–4.

[66] Yuan YP, Cao XL, Lei B, Zhang D. Heat transfer of ground heat exchanger for GSHP (4): system characteristics in coupled operation. Heating Ventilating & Air Conditioning 2010;40(5):114–7.
[67] Wang HJ. Study on operating performance and dynamic simulation of ground-coupled heat pump system. Tianjin: Tianjin University; 2004.
[68] YX Qu, Modeling and Simulation for Ground Source Heat Pumps System, Xi' an University of Architecture and Technology, Xi' an, 2004.
[69] Zhao J, Wang HJ, Song ZK, Chen ZH, Li XG. Experimental and grey prediction on the long-term behavior of U-shaped ground coupled heat exchangers. Acta Energiae Solaris Sinica 2006;27(11):1137–41.
[70] Wang HJ, Zhao J, Shen L. Experimental investigation on long-term performance of ground source heat pump system. Journal of North China Electric Power University (Natural Science Edition) 2007;34(2):52–4.
[71] Ma HQ, Long WD. Ground heat balance in GSHP. Heating Ventilating & Air Conditioning 2009;39(1):102–6.
[72] Yang WB, Shi MH, Chen ZQ. Experimental study on operation characteristics of ground coupled heat pump operated in cooling and heating mode. Journal of Southeast University (Natural Science Edition) 2009;39(2):276–81.
[73] Liu WX, Tang ZW, Wei JX, Zhang HY, Ma CF. Experimental study on periodic heating operation of ground source heat pump. Renewable Energy Resources 2008;26(1):59–61.
[74] Wang Y, Fu XZ. Load characteristics and characteristic parameters influencing the performance of GSHP systems. Heating Ventilating & Air Conditioning 2008;38(5):48–55.
[75] Zhao J, Wang HJ. Numerical simulation on heat transfer characteristics of soil around foundation pile-buried underground heat exchangers. Heating Ventilating & Air Conditioning 2006;36(2):11–4.
[76] Yu ZY, Hu PF, Yuan XD. Experimental study on ground heat exchangers heat transfer in ground source heat pumps. Journal of Huazhong University of Science and Technology (Urban Science Edition) 2008;25(3):157–60.
[77] Gao Q, Qiao G, Yu M, Bai JY. Ground temperature property and restorative characteristics to enhance heat transfer in GSHP. Journal of Refrigeration 2003;3:38–41.
[78] Gao Q, Li M, Yu M. Experiment and simulation of temperature characteristics of intermittently-controlled ground heat exchangers. Renewable Energy 2010;35:1169–74.
[79] Gao Q, Li M, Qiao G, Yu M, Xuan ZH. Restorative characteristics of ground temperature and simulation analysis of behavior. Journal of Thermal Science and Technology 2004;3(3):224–8.
[80] Cui P, Diao NR, Fang ZH. Analysis on discontinuous operation of geothermal heat exchangers of the ground-source heat pump systems. Journal of Shandong Institute of Architecture and Engineering 2001;16(1):52–7.
[81] Liu XY, Zhang SY, Hu MM, Ding Y. Experimental research of ground-source heat pump for heating and cooling through supplies in winter and summer. Construction Machinery for Hydraulic Engineering & Power Station 2002;21(1): 14–22.
[82] Liu J, Zhang X, Gao J, Li KS. Research of soil temperature restoration characteristics of ground-source heat pump systems. Heating Ventilating & Air Conditioning 2008;38(1):147–50.
[83] Yang WB, Shi MH, Dong H. Numerical simulation on performance of alternate operation of solar-earth source heat pump system. Journal of Thermal Science and Technology 2005;4(3):228–32.
[84] Wang JG, Sun PJ, Wang HX, Yang B, Yan F. The feasibility study of hybrid gshp with supplemental heat rejecter. Journal of Hebei Institute of Architectural Science and Technology 2005;22(3):8–10.
[85] Liu J, Wang JG, Kang LG. Feasibility of using composite ground source heat pump in hot summer and cold winter region. Journal of Hebei University of Engineering (Natural Science Edition) 2008;25(3):81–3.
[86] Yang WB, Shi MH. Study on hybrid ground source heat pump system. Building Energy & Environment 2006;25(3):20–6.
[87] Yang WB, Shi MH. Optimization of solar-ground source heat pump systems based on genetic algorithm. Heating Ventilating & Air Conditioning 2007;37(2): 12–7.
[88] Yu YS. Study on the performance characteristic of the integrated frozen of the soil thermal storage and ground-coupled heat pump system. Harbin: Harbin Institute of Technology; 2004.
[89] Yao Y, Ma XL, Yu YS. Study on the integrated frozen of the soil thermal storage and ground-coupled heat pump system. Fluid Machinery 2004;32(6): 48–51.
[90] Yu YS, Ma XL, Yao Y. Performance of cool charge and discharge processes in an integrated soil cool storage and ground-coupled heat pump system. Heating Ventilating & Air Conditioning 2004;34(5):1–6.
[91] Yu YS, Ma XL, Yao Y. Simulation of integrated soil thermal storage and ground-coupled heat pump systems. Heating Ventilating & Air Conditioning 2005;35(6):1–5.
[92] Yu YS, Ma XL, Yao Y. Application of the solid phase increasing method in simulation of soil charge and discharge processes. Heating Ventilating & Air Conditioning 2005;35(8):20–4.
[93] Yu YS, Ma XL, Yao Y. Simulative research on soil thermal storage in integrated soil thermal storage and ground-coupled heat pump system. Acta Energiae Solaris Sinica 2004;25(6):820–5.
[94] Man Y, Yang HX, Fang ZH. Study on hybrid ground-coupled heat pump systems. Energy and Buildings 2008;40:2028–36.
[95] Jia Y. Study on the system optimization and the operation control strategies for hybrid ground source heat pump systems. Chongqing: Chongqing University; 2011.
[96] Gang WJ, Wang JB. Study on predictive control of hybrid ground source heat pump system. Renewable Energy Resources 2012;30(1):97–101.